INTERIM REPORT ON ENVIRONMENTAL EFFECTS OF HAUL ROADS

SURFACE ENVIRONMENT . MINING
SEAM
USDA FOREST SERVICE PROGRAM

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INTERIM REPORT ON

ENVIRONMENTAL EFFECTS

OF HAUL ROADS

PART 1: GENERAL

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PART 2: A SIMPLIFIED MODEL OF THE DAMMING EFFECTS OF
EMBANKMENTS ON GROUNDWATER

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INTRODUCTION

This report has been written in fulfillment of the Proposal for the Continuation of SEAM Engineering Research in Transportation, dated June 1975, under SEAM Research Agreement entitled "Development of a Methodology for Identifying and Quantifying Potential Environmental Impacts of Alternative Transportation Systems Applicable to Surface Mining" (INT Grant No. 18). The report reflects changes in objectives as stated in Amendment No. 1 to INT Grant No. 18, which essentially limits the scope to haul roads and water resources. It will be the first step toward establishing the correct mathematical expressions which will be used to calculate quantitative estimates of the impacts on the water resource and fugitive dust by transportation system characteristics in interaction with the corridor environment characteristics. This work is continuing under a cooperative agreement (Supplement No. 45) with the SEAM Engineering Research Program.

Quoting from the cooperative agreement, the objectives of the research are to examine the following impacts:

1. Water-polluting emissions and discharges including sediment, chemicals, salts, oils, and water temperature effects.

2. Hydrologic changes produced by the transportation system, independent of water quality. This involves changes in the amount of surface and subsurface water and its distribution in both space and time.

3. Fugitive dust as a result of entrainment of dust by wind blowing across the road surface and cut-and-fill surfaces.

It is emphasized that these examinations are to be accomplished through literature search, review of other related research and communications with other researchers. No field data are to be generated by the MSU civil engineering group.

The contents of this report are divided into two parts. Part 1 consists of four subdivisions--hydrology, sedimentation, fugitive dust, and chemical. Although intricately related, particularly the latter three under water quality, the four are treated separately, at this time, to facilitate formulation of a model framework for each. In addition, fugitive dust is considered from an air impact viewpoint. Essentially, Part 1 gives the end results of the information search, showing the model structure(s) that have the most promise for further evaluation, modification and integration for haul road conditions. Details of all facets of the search, i.e., complete literature review, are not given. Too, much of the lengthy stage-setting dialogue, such as the basic mechanics of soil erosion, is omitted. Comprehensive treatments of such material can be found in the cited references.

Although Part 2 falls under the subject heading of hydrology, it is given separately. This section contains extensive preliminary work in the development of a specific model to predict the damming effects of embankments on groundwater.

In summary, this report is an interim one-year progress report which outlines the status of the project and points the direction of further study. In essence, the results are given in a basic framework that will require extensive adaptation to haul road conditions. As might be expected, direct applicable data and methods are not yet developed for the well-established highway system of the United States. Utilization of agriculturally-based information is, therefore, a necessity, resulting in a formidable list of objectives facing this research project.

PART 1

GENERAL

Each of the following subdivisions contains its own introductory remarks. As an overall introductory comment, a definition of haul road, as perceived by the authors, is in order. Historically, a surface mining haul road has created images in one's mind of a crude trail or path resulting from wear of the vehicle wheels. In contrast, today a haul road is envisaged as a fairly sophisticated transportation network. In the future, such networks may locally approach, in scope and standard, the secondary and even primary highway systems of today. If production of coal and other minerals is to attain the forecasted levels, well-designed road systems will be required. The modeling efforts are progressing with this in mind. In addition, the efforts reflect a general case, in hopes that developed methodologies will apply to an alpine environment as well as a semi-arid coal field condition. For example, perennial streamflow parameters may not be applicable to a small watershed near Colstrip, Montana, but should still be included in the general hydrologic model.

HYDROLOGY

Before looking closely at the subject of transportation projects and their impact on water quality, it is necessary to look at the precipitation phase of the hydrologic cycle to better understand the physical effects of our activities upon hydrologic processes.

Precipitation primarily occurs as rain or snow. Upon reaching the earth's surface, this precipitation is utilized in a number of processes. The precipitation may generate surface runoff, evaporate back to the atmosphere, infiltrate into the soil, or be transpired by the vegetation. For a specific storm, there is a combination of potential uses for the precipitation received. The relative magnitude of each use will vary with the individual storm. This interplay of water and the environment is called the hydrologic cycle.

The hydrologic cycle is usually depicted as a set of dynamic components or pathways for the movement of water. The primary components are precipitation, surface runoff , surface detention storage, soil water storage, underground or subsurface storage, and evapotranspiration. A water balance equation can be used to relate these parameters in the following manner (1):

$$Q = P - ET \pm GW \pm SW \pm SS$$

where; Q = Streamflow

P = Precipitation received in the area

ET = Evapotranspiration (a combination loss of water vapor to the atmosphere by evaporation and plant transpiration)

GW = change in groundwater storage

SW = change in soil water storage

SS = change in surface storage

In the various climatic and vegetative life zones the relative magnitude of these parameters will vary. Their characteristics can also be modified by man's activities such as irrigation, logging, urbanization and damming.

Any man-made changes in a drainage basin or watershed such as the construction and maintenance of a transportation system can affect both the microclimatic and hydrologic properties of the watershed. The hydrologic significance of the transportation system will depend in part upon the proportion of the total watershed area which is disturbed or modified. The microclimatic changes resulting from such a facility may affect a larger area than that actually occupied by the right of way.

Transportation systems can have direct effects upon the microclimatic properties of a site. The removal of vegetation, especially trees, will affect the accumulation and redistribution patterns of snow by wind. Grubbing or modification of vegetative cover will also affect the air and soil temperature characteristics of the site. These temperature effects can change evaporation rates from the soil and transpiration rates from the vegetation. If there is insufficient soil water to satisfy these increased evapotranspiration demands then drought will occur. Some plant species in the areas affected by the right of way may not be able to adapt to the more extreme microclimatic changes created by the transportation system. These intolerant plant species will then have a lower productivity and in extreme cases they may be replaced by less desirable species.

A transportation system can also have a wide range of effects on the hydrologic properties and processes. Compaction of the soil will influence both the infiltration rates of water and the percolation rates of the soil water and the groundwater (Part 2 will deal with this). The removal of vegetation along the right of way will eliminate transpiration and the interception storage of precipitation and associated evaporation. Direct

rainfall on the bare soil surfaces will also modify the soil infiltration characteristics by the "puddling" process. "Puddling" is caused in part by raindrop splash which reorients surface particles and washes finer materials into the soil which lowers porosity. Overland flow rates are also increased due to the removal of surface roughness created by vegetation and vegetative debris or litter. The surface storage component is also diminished by the removal of vegetation.

The basic surface runoff characteristics for the watershed can also be modified by a transportation facility. The time of concentration for surface runoff would be changed due to the presence of impervious areas and alterations in the vegetative composition. The changes in time of concentration would affect the peak discharge characteristics for a storm. The total runoff volume or discharge for the storm would also be increased. Increases in peak discharge and total discharge would create a change in the flow regime of natural drainage ways in the watershed.

Hydrologic Modeling

Many complex and interrelated changes can occur to the hydrologic properties of a watershed due to the construction and maintenance of a transportation facility. In recent years hydrologists have been developing computer models to simulate the complex water balances for watersheds. The utilization of such a model for predicting the impacts of a transportation system on the hydrologic properties of watershed could enable designers to minimize the total amount of disturbance.

There are basically two types of simulation models. They are known as deterministic models and stochastic models. Deterministic models attempt

to represent the known hydrologic processes that occur in a watershed to project future events. Stochastic models utilize the statistical properties of existing records and probability laws to generate future events. Deterministic models are the most appropriate for interpretation on a micro scale or if there are secondary processes that are dependent upon the primary processes of the model. With a deterministic model, the appropriate parameters can be modified to test the effects of man-made changes on the water balance of a watershed.

One of the most widely accepted deterministic models currently in use is the Stanford Watershed Model IV (2). Two newer modifications of this model are the Texas Watershed Model (3) and the Kentucky Watershed Model (4). The Kentucky Watershed Model OPSET (optimal setting of parameters) is a self calibrating version to provide ease and uniformity in calibration of the model to specific watersheds.

There are two primary stages in model development for a watershed. The first is to calibrate the model to accurately predict the runoff with existing conditions from known precipitation events. This calibration process would determine which watershed parameters are significant in the later modeling processes.

The second stage of model development is to determine the changes in runoff quantity due to alteration of the watershed by the construction of the proposed facility. Various inputs to the model such as watershed canopy cover, percent of impervious area, and the change in infiltration rate would be altered based on characteristics of the transportation system such as cleared right of way, amount of pavement, and compaction of soil.

Changes would also be necessary in the stream routing portion of the model due to alterations of the natural drainage patterns by the construction of system drainage.

This discussion does not specify the use of a particular model. At this time a number of models are being compared to determine which ones might be the most versatile in testing the effects of transportation systems on the hydrologic properties of watershed.

Another potential method for estimating transportation system impacts is the possible adaptation of state highway hydraulic design formulas. In the Rocky Mountain States hydrologic data do not exist for a large number of the smaller watersheds which would be affected by transportation systems. State highway hydraulics manuals are therefore used to estimate the return period floods for drainage structures based on minimal data about the hydrologic properties of an area. These formulas may be adaptable for a simplistic analysis of transportation system impacts on the watershed.

The Montana State Highway Department utilizes flood frequency curves developed by Dodge (5). Dodge used linear regression analysis to divide the state of Montana into contiguous flood regions with an appropriate flood prediction equation for each region. The prediction equations are of the form:

$$Q_1 = b_o X_1^{b_1} X_2^{b_2} \cdots X_n^{b_n}$$

where Q_1 = peak flow

b_o = regression constant

$b_1, b_2, \cdots b_n$ = exponents developed from regression

$X_1, X_2, \cdots X_n$ = independent variables

From the prediction equations generated with the above analysis, a total of six watershed parameters was found to be significant in the return period flood. Not more than three of these parameters are significant in a single flood region. The parameters are:

1. A = drainage area (mi^2)
2. F = percent forest cover (%)
3. % > 6000 = percent of area greater than 6000 ft elevation (5)
4. PS = SCS Mean annual precipitation (in.)
5. I = precipitation intensity, 2 yr - 24 hr (in./24 hr)
6. S = soil storage index (in.)

The individual regression constant (b_o) and exponents ($b_1, \cdots b_\eta$) are listed by design flood (i.e., $Q_2, Q_{10} \cdots Q_{50}$) for each region so that a determination of design floods is very rapid once the necessary watershed parameters have been determined. For example, the two year return period flood (Q_2) equation for the Bozeman, Montana flood region would have the following form:

$$Q_2 = .00172(A)^{0.97}(PS)^{1.39}(F)^{0.758}$$

(for % forest > 19%)

The watershed area (A) and percent forest cover (F) can be determined for the watershed from topographic maps or interpretation of aerial photos. Dodge has also produced a nomograph system of flood prediction chart for each flood region of the state of Montana.

Addition of more factors to these equations to allow for transportation facility effects on the design flood may be possible. The addition of

these factors is being investigated in the following equation:

$$Q_s = Q_\eta(1+(I_oA_1+CA_2))$$

where; Q_s = peak flow of watershed with transportation system

Q_η = design year peak flow in undisturbed watershed (Dodge)

I_o = runoff factor for impervious areas in system

A_1 = % of total watershed area in right of way which is impermeable

C = compaction-infiltration factor for permeable portions of right of way

A_2 = % of total watershed area in right of way which is permeable

This approach superimposes the hydrological properties of the transportation system onto the design flood of the undisturbed watershed. The reason for this is to maximize the potential effects of the system to see if it would significantly affect the natural hydrological balance of the watershed.

To determine the effects of a transportation system on the total runoff from a watershed, a synthetic hydrograph development would be necessary for the ungaged watershed. One approach for development of the synthetic hydrograph is presented in the Soil Conservation Service (SCS) National Engineering Handbook, Section 4, Hydrology (6). This technique estimates the direct runoff based on watershed parameters and the amount of rainfall. Direct runoff is determined with the formula:

$$q = \frac{(I-0.2S)^2}{I+0.8S}$$

where; q = direct surface runoff in inches

I = storm rainfall in inches

S = soil index

The soil index is determined by a method outlined in the SCS handbook. The SCS recommends that 6 hours be used as the minimum storm period. In this procedure, the runoff hydrograph is synthesized by the relationship of direct runoff to the time of concentration and a series of dimensionless hydrographs. This method might be modified in the time of concentration and direct runoff portions of the relationship to assess the impacts of a transportation system on the hydrological properties of the watershed.

Understanding the hydrologic processes will then allow us to delve into the water quality aspects of surface mining and transportation systems.

WATER QUALITY

Changes to aquatic systems resulting from the impact of transportation projects occur in the form of physical, chemical and biological pollution, and in alterations to the physical equilibrium of the system involving such parameters as temperature, flow, and boundary conditions.

Effects of these changes are exhibited primarily in water quality, the aesthetic appearance of the aquatic system, and the structure and form of the aquatic ecosystem (1). Most of these changes are felt both locally and by the downstream user. The extent of the effect of altered water quality is, of course, dependent on the character of the downstream user--

household, agricultural, industrial or recreational. Effects are only generally discussed in this paper.

In the following discussions, water quality is viewed primarily from a physical aspect, namely erosion-sedimentation. To a lesser extent, the subject of chemical water quality is discussed. At the present time, there exists considerably more information on erosion-sedimentation. In all cases, the key word is quantify, that is, determine how much pollution or degradation occurs because of a transportation facility.

Erosion-Sedimentation

In general, the greatest and most easily perceived impact to aquatic systems caused by transportation projects is that of siltation of the systems (1). This occurs due to the erosion from freshly exposed and disturbed land surface with subsequent transport towards the stream by overland flow and downstream sediment transport to the point where the final impact is felt.

Impacts of erosion of back slopes, ditches and untreated road surfaces, during and following construction, have long been recognized. Sedimentation of streams have detrimental effects upon aquatic life, aesthetics, and the use of water in man's activities. In addition to direct physical effects on fish, chain effects are now recognized such as increased stream turbidity reduces light penetration which inhibits the process of photosynthesis which means less food and less aquatic organisms. Obvious effects of sedimentation-clogged culverts and ditches, slides--cost millions of maintenance dollars each year. Increased awareness of these effects have

had a corresponding increase in efforts to reduce erosion on road and other construction projects.

Until recently, efforts to combat erosion have consisted of physical features constructed in an improvised manner during the course of a project. Planned erosion control measures such as post-project seeding and mulching, and ditch treatments have been implemented somewhat arbitrarily. Quantitative effects of these methods have been at best, estimated or subjectively described. The need has arisen to determine the amount of sediments that will result if a specific project is constructed. Reasonable advance estimates of erosion potential will give the transportation system planner another tool in assessing alternative routes. Once a route is selected, an erosion control plan can be formulated prior to the letting of bids for a project. A bid item for erosion control can then be competitively bid upon and implemented. The State of Maryland currently is doing this rather successfully. The State uses a methodology, that will be discussed in this report, to establish soil loss in tons/acre for a specific project at various stages of construction. If the loss exceeds the specification of 15 tons/acre, average annual value, then control measures are included in the contract. In general, projects in Maryland undergo preventative treatment throughout construction. For example, exposure of raw cuts and fills cannot exceed ten vertical feet without erosion control treatment. Acceptance of the regulatory method has been good, as long as it is built into the competitive, consumer-pays system (2).

Universal Soil Loss Equation

Prediction of soil losses under construction conditions is a relatively new field. During the year of this report, extensive information searches were performed through the Federal Highway Administration computer bank, several state highway departments, other universities, Department of Agriculture, and the Environmental Protection Agency. These searches, along with numerous telephone and personal discussions with erosion experts (3,4,5) have resulted in the selection of the universal soil loss equation (USLE) for adaptation to this research project. This empirical erosion equation was developed by the Agricultural Research Service and is now widely used on farmland. Major factors in soil erosion and their functional relationships to soil loss have been identified and established. The factor relationships were derived from statistical analyses of soil loss and associated data obtained in 40 years of research by ARS and assembled at the ARS runoff and soil-loss data center at Purdue University. The data include more than a quarter-million runoff events at 48 research stations in 26 states, representing about 10,000 plot-years of erosion studies under natural rain. They also include supplemental data obtained with rainfall simulators on field plots and from fundamental studies in the laboratory (3).

Modification of the soil loss equation to non-farm uses has been demonstrated in the past two years. Wischmeier (3), Meyer and Ports (4), and Foster (5) have led the way in adapting the USLE for use in construction areas. The states of Maryland (6), California (7), Virginia (8), Arizona (9), Pennsylvania (10), and the Transportation Research Board (11), have included the USLE in their endeavors against soil loss.

The companion processes of soil erosion and sedimentation involve many factors that influence the detachment, transportation, and deposition of soil particles by water (or wind)(4,12,13). The rate of upland soil erosion depends on the erosiveness of the rain, the erodibility of the soil, the length and steepness of slope, the cultural practices used, the stage of crop growth, and the supporting conservation practices applied to the land. These erosion influencing factors have been combined in the Universal Soil Loss Equation as follows (4):

$$A = RKLSCP$$

where; A = computed soil loss, usually in tons per acre. It is an estimate of the average annual interrill plus rill erosion from rainstorms for field size areas. It must be increased to account for additional erosion from gullies and streambanks along the flow route and/or decreased to account for deposition of eroded soil within the watershed.

R = the rainfall factor, accounts for differences in rainfall intensity, duration, and frequency at different locations. It is usually expressed in average units of rainfall erosivity index, EI, the total of the kinetic energy of each rainstorm times the storm's maximum 30-minute intensity, annual R-factor values have been determined for most locations, east of the Rocky Mountains (14). Western United States, Alaska and the Islands have recently been included in R-factor maps (11). The R-factor does not account for soil losses due to snowmelt and wind erosion. Seasonal variations in R-factor are taken into account in R-factor distribution curves (14).

K = the soil erodibility factor, is a measure of the susceptibility of a given soil to erosion, expressed in tons per acre per EI unit. The K factor represents the infiltration characteristics of a soil, and its capacity to resist detachment and transport by rainfall and runoff. K factor values have been obtained experimentally for a few soils and estimated for numerous other soils throughout the United States. Values range from about 0.7 for highly erodible loams and silt loams to less than 0.1 for sandy and gravelly soils with high infiltration rates. For soils with unknown K values, a nomograph has

been developed by Wischmeier (15)(Fig. 1) to estimate erodibility. Using particle size distribution in the silt and sand ranges and the organic matter content, the nomograph will give a first approximation of K. Further refinement of the K-value from the nomograph is obtained using a structural class parameter and permeability. The nomograph is not recommended for use on soils with greater than 50 percent clay content.

L = the slope length factor. Soil loss is related to the degree, length and curvature of the slope. Effects of curvature or other irregularities in slopes have not been extensively evaluated. Foster (16) has proposed a technique for evaluating irregular field or construction site slopes. Irregular slopes can be utilized to combat erosion and should, therefore, be included in the model. The Agriculture Handbook (14) recommends the following formula for determining the length factor for uniform slopes:

$$L = \left(\frac{\lambda}{72.6}\right)^m$$

where; λ = slope length, ft

m = 0.5 for slopes less than 10%

0.6 for slopes greater than 10%

Foster's method modifies this basic equation by dividing the irregular slope into a series of segments such that the slope steepness and soil type, and thereby the soil detachment rate, within each segment could be considered to be uniform. Total soil loss is thus obtained by integrating the losses of the segments. The State of Maryland is currently applying this method to actual construction sites (4).

S = the slope-steepness factor, accounts for the increased erosiveness of runoff and ease of sediment movement as slope steepens. Smith and Wischmeier (17) recommend the following formula for S:

$$S = \frac{(0.43+0.30s+0.043s^2)}{6.613}$$

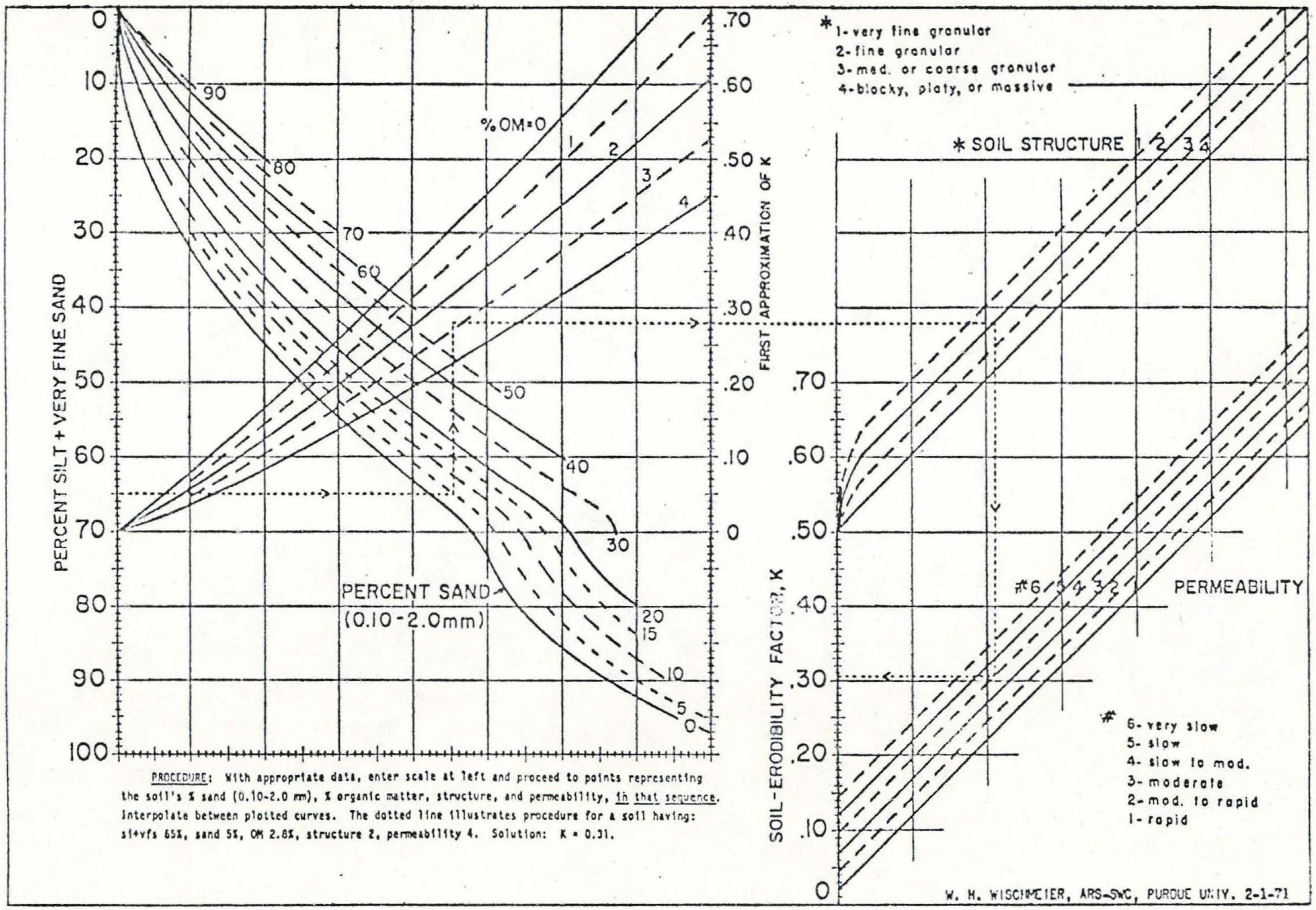

Figure 1. Soil erodibility nomograph.

where; S = degree of slope in percent

In application, L and S are commonly combined into a dimensionless topographic $\overline{LS}$ factor and are obtained from a nomograph, Fig. 2, or by use of the combination equation $\overline{LS} = \sqrt{\lambda}\ (0.076+0.0053\,s+0.00076\,s^2)$. There is a limitation in that a maximum slope of 20% (5:1) can be applied in the nomograph. Ports (4) and Swerdon (10), Fig. 3), have extrapolated the equation to include slopes up to 100% (1:1) for highway back slopes.

C = the dimensionless cropping-management factor. The first three terms of the soil loss equation, RKLS, define soil loss from a particular location with a given length and degree of slope, for a continuous fallow condition. The term C is the beginning of soil loss reductions and is the result of vegetation management. For a bare, cultivated soil with a relatively smooth surface, C=1.0. Mulches, such as straw, stone and wood chips, can reduce C to only a small percentage of that for bare soil. The C-factor for a good sod is essentially zero (4). On most sites, the greatest opportunity for reducing erosion is by using land management practices to reduce the C-factor.

P = the dimensionless erosion control practice factor accounts for the effect of conservation practices such as interceptor terraces and contour strip of vegetation. When no such practices are used, p=1.0. While the USLE is designed to handle such practices, they are farming oriented and not directly suited to highway engineering. In highway work the obvious supporting practice is the provision of a buffer strip between the eroding strip and the receiving water (10). If sediment-bearing runoff can be directed over a forest floor, for example, some sediment will remain trapped in the litter with lessened effect on water quality (18). While a betterment to water quality results, the authors question this sweep-it-under-the-rug approach. However, in practice, 100 percent reduction in soil erosion may not be possible and entrapment sediment within a watershed may be necessary. Applying the USLE to a particular watershed would then include a sediment delivery ratio, the ratio of the sediment leaving the watershed to gross erosion on the watershed. The flattening of natural slopes of their lower portions, which encourages deposition, would constitute such an entrapment.

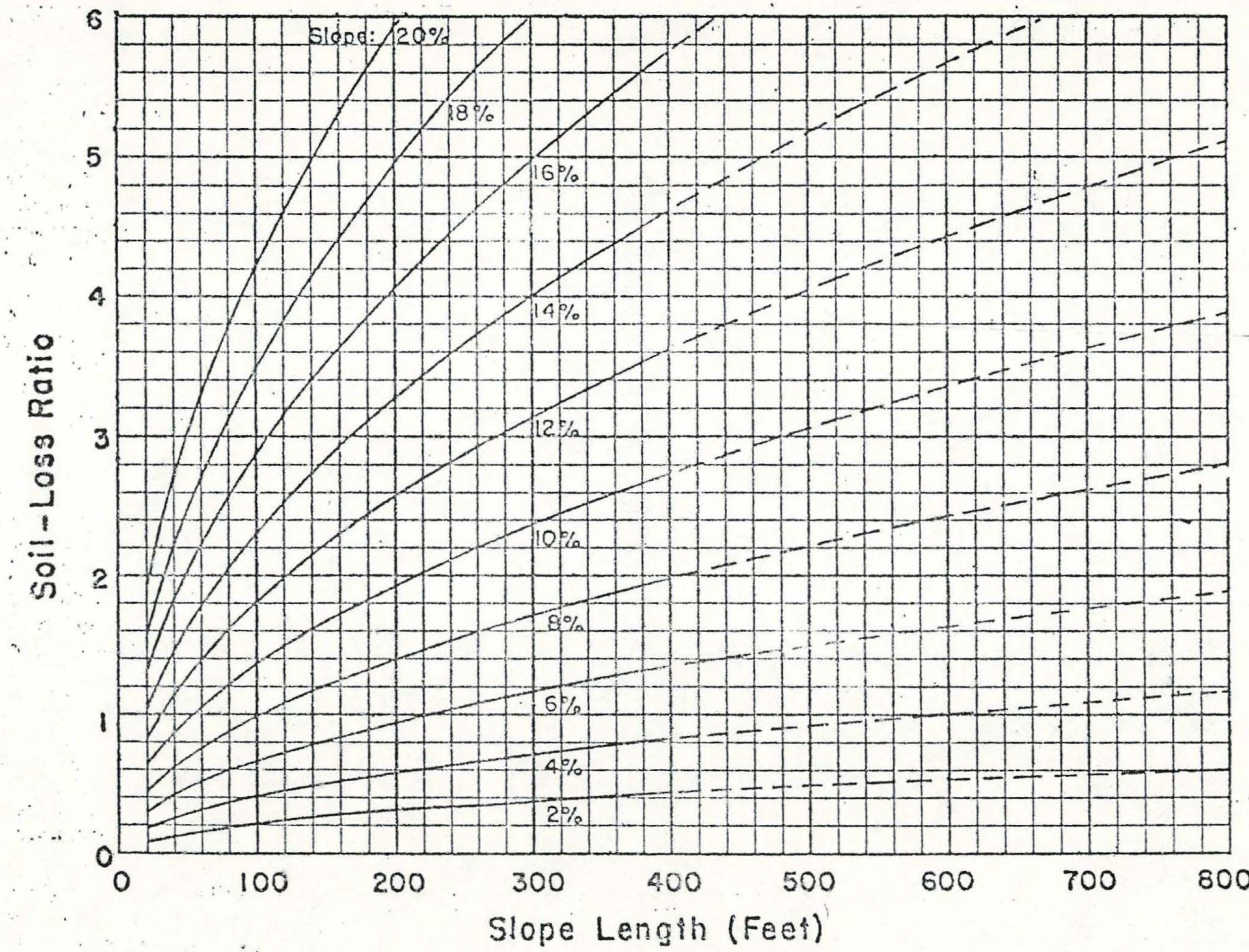

FIGURE 2.—Slope-effect chart (topographic factor, *LS*).

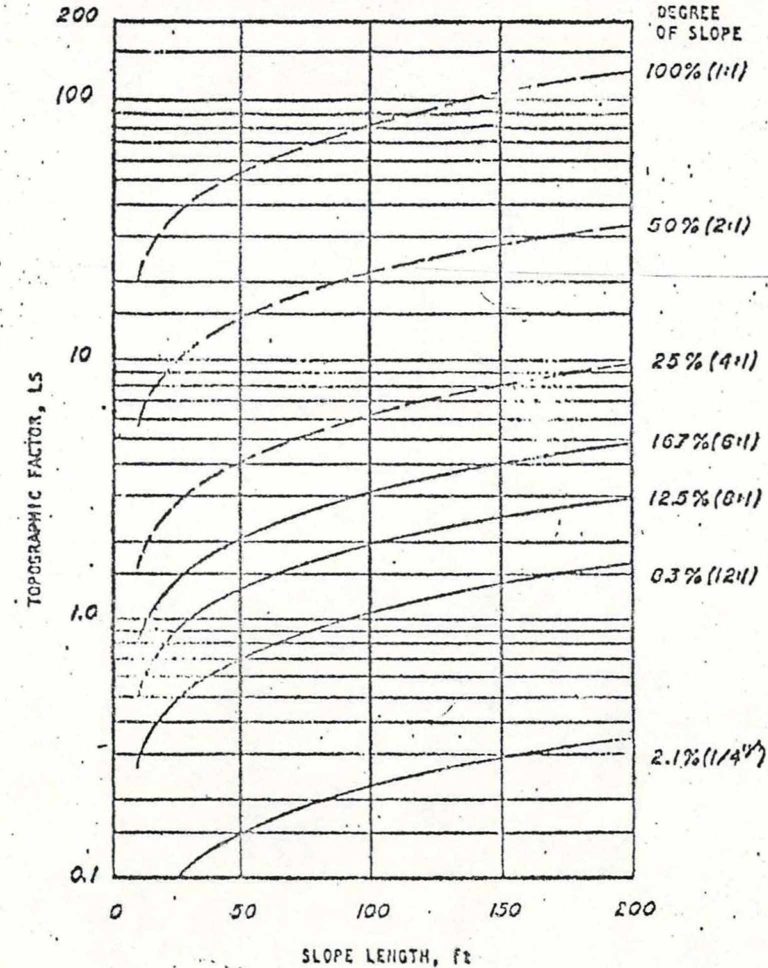

FIG. 3 Topographic factor LS, slope effect. Dashed lines are extrapolated values.

Examples of application of the universal soil loss equation will be given in later reports when adaptations have been accomplished for haul road conditions. Recommendations will follow, which will discuss the modifications necessary to accomplish such a task.

Summary and Recommendations

The universal soil loss equation is a proven, simple-in-form, model that has been utilized extensively in agriculture. Its use in construction and highway engineering, though minimal, shows promise; thus, capitalizing on the agriculture effort seems prudent. There are, however, portions of the equation that are in need of scrutiny and evaluation to assure proper application to haul roads and surface mining.

The basic soil loss equation , A=RKLSCP, gives the user the average annual interrill plus rill erosion, and cannot be applied to a single storm event. Do the unique topography, semi-arid conditions and storm severities of the West require that single storms be scrutinized or are they included in the average annual value? The corresponding gully erosion from such storms will require a method to estimate amount of sediment and relative contribution to total load.

As expressed in the report, the equation has no provision for effects of snowmelt. Runoff from snow, in certain areas of the West, exceed rainfall runoff and may cause the greater share of erosion. The Soil Conservation Service of USDA has recently published "Technical Notes" (19) that include snowmelt runoff when computing the R-value of the equation. Ref. (19) deals only with Montana and additional publications, covering other states, are being sought for review.

The R-value of the soil loss equation is usually obtained from iso-erodent maps. The map, covering east of the Rocky Mountains (14), has received considerable attention and use throughout several years. In contrast, the Rocky Mountains and areas west have only recently had iso-erodent maps developed. With no proven history, these maps will require evaluation. In addition, the diverse topography of the West may cause large variations in local precipitation patterns, thereby requiring considerable judgement and improvisation when using the maps. Determination of an R-value may require a modeling effort in itself.

Likewise, the irregular, upheaved topography of western mining lands may present more difficulty than uniform farmland when selecting a soil erodibility value, K. Use of the soil erodibility nomograph, Fig. 1, will need to be evaluated for applicability to surface mining lands. Local changes in the K-value has been circumvented in Ports' (4) applications in Maryland by selecting the worst value on a project and applying it to the entire project. This may be all right in design application, however, in assessing environmental impacts, relative quantification may be necessary. Also, the use of the nomograph entails two parameters, soil structure and permeability, in somewhat subjective terms. These terms, familiar to agriculturalists, could be further clarified to avoid mis-use by engineers and planners.

Research has been done to relate subsoil erodibility to chemical, mineralogical and physical paramters (20). Results of this research did not improve upon the nomograph of Wischmeier. The research did aid in selection of K-values for high clay soils. Recall that the Wischmeier

nomograph is not applicable to soils with clay content exceeding 50 percent.

Selection of the topographic LS-factor from Fig. 2 is limited to slopes less than 20 percent (5:1). To this point, research data support the family of curves; but beyond 20 percent, the curves have been extrapolated mathematically (10,19,21). The extrapolated curves will be evaluated for application to the objectives of this project.

In short, extensive research is needed to adapt the universal soil loss equation, developed for farming soil, terrain and climatic conditions, to western surface mining areas that have a broad range of soils, terrain and climates, which change appreciably with relatively small shifts in location.

Chemical Quality

It has been determined that runoff from road and street surfaces can be highly contaminated. In a hypothetical city street example, the runoff from the first hour of a moderate-to-heavy storm would contribute more pollutant load than that city's sanitary sewage during the same time period. These calculations were made for a situation in which the streets were cleaned either intentionally or by rainfall on the average of once every five days. Thus, this large discharge of contaminated runoff could occur many times in a single year (1).

Much research has been conducted to determine what types of contaminants can be expected from roadways. A great deal is known about the potential water quality hazards of these substances and their maximum

permissible levels in water supplies. However, little work has been done to relate the total impact of these road surface pollutants on the water quality of a watershed. Even on a rural transportation system the effect of these pollutants can be significant. This is especially true if these contaminants are flushed into a stream during periods of low flow when there is insufficient water to maintain contaminant concentrations below critical levels.

Table 1 lists the street surface contaminants and deposition rates from vehicles which were identified by Shaheen (2) for the Washington, D.C. area. Other contaminants can be found on roadways but they may be present as a result of the local geology. Another possible source of contaminants could result from specialization of the traffic such as spillage of payloads on mine haul roads. Large point source pollution can also occur from accidents involving heavy transports. Exposure of geologic strata which contain abnormally high concentrations of potential contaminants must also be considered during the planning phases of a transportation system.

Most highway departments attempt to maintain a relatively ice-free road surface for safety purposes. As a result large amounts of sodium chloride and calcium chloride are spread on the roadways. A 1971 EPA study found that many streets and roads may receive more than 20 tons of deicers per lane mile per year (3). These salts can cause damage across a wide environmental spectrum and may have prolonged residual effects on soils and vegetation. A number of incidents and detailed studies have also been published about the adverse effects of deicing salts to public water supplies and receiving waters (4).

TABLE 1. DEPOSITION RATES AND COMPOSITION OF TRAFFIC-RELATED ROADWAY DEPOSITS[a]
(WASHINGTON, D.C. METROPOLITAN AREA)

	Dust and Dirt		--
	Deposition Rates (Units -- Unless otherwise stated)		Composition (% by Weight Unless Otherwise Stated)
Parameter	lbs/axle-mile	g/axle-km	
Dry Weight	2.38×10^{-3} 6.33×10^{-4}	6.71×10^{-1}	--
Volume	(quarts/axle-mile)	4.33 (l/axle-km)	--
Volatile Solids	1.21×10^{-4}	3.41×10^{-2}	5.1
BOD	5.43×10^{-6}	1.53×10^{-3}	0.23
COD	1.28×10^{-4}	3.61×10^{-2}	5.4
Grease	1.52×10^{-5}	4.29×10^{-3}	0.64
Total Phosphate-P	1.44×10^{-6}	4.06×10^{-4}	0.061
Nitrate-N	1.89×10^{-7}	5.33×10^{-5}	0.0079
Nitrite-N	2.26×10^{-8}	6.37×10^{-6}	0.00095
Kjeldahl-N	3.72×10^{-7}	1.05×10^{-4}	0.016
Chloride	2.20×10^{-6}	6.20×10^{-4}	0.092
Petroleum	8.52×10^{-6}	2.40×10^{-3}	0.36
n-Paraffins	5.99×10^{-6}	1.69×10^{-3}	0.25
Asbestos	$3.86 \times 10^{+5}$ (fibers/axle-mile)	$2.40 \times 10^{+5}$ (fibers/axle-km)	3.6×10^{5} (fibers/gram)
Rubber	1.24×10^{-5}	3.50×10^{-3}	0.52
Lead	2.79×10^{-5}	7.87×10^{-3}	1.2
Chromium	1.85×10^{-7}	5.22×10^{-5}	0.008
Copper	2.84×10^{-7}	8.01×10^{-5}	0.012
Nickel	4.40×10^{-7}	1.24×10^{-4}	0.019
Zinc	3.50×10^{-6}	9.87×10^{-4}	0.15
Magnetic Fraction	1.26×10^{-4}	3.55×10^{-2}	5.3

(a) Numerous other pollutants were found in urban roadway samples; however, those listed in the table were the only ones related to motor vehicular traffic.

Of the many contaminants listed in Table 1 by Shaheen, lead is considered as potentially one of the most toxic substances due to its residual effects on mammals. The largest single use of lead is as an antiknock compound in gasoline. Upon combustion most of this lead is emitted to the atmosphere as particulates. Areas immediately adjacent to a roadway receive the highest concentrations of the lead particulates. Quarles, et al. (5) found increasing concentrations of lead with decreasing distance from a highway in the soil, vegetation, and small mammals in a study conducted in Virginia.

Much work has been done on the movement of pollutants on agricultural lands where direct applications of pesticides, herbicides, and fertilizer are made to irrigated crops. However, little work has been done on the movement of contaminants from road surfaces. The most promising approach to this problem is the adaptation of this agricultural research to hydrologic models that are modified to assess transportation system impacts.

Agricultural chemicals such as fertilizers, pesticides, and herbicides are considered as pollutants when they are transported away from the place of application. This transport will occur primarily by water and in most instances downstream water is the destination of these contaminants. Frere (6,7) has presented a model which follows the potential pathways of a chemical in a watershed (Fig. 4). In each hydrologic compartment of the model certain chemical processes are recognized which can have an effect on the pollutants. These processes are adsorption, degradation, and volatilization. This model is very realistic in tracing the movements of chemicals in a watershed. Table 2 is a listing of the parameters needed to operate the model (7).

PATHWAYS OF CHEMICALS IN THE SOIL-WATER-PLANT SYSTEM

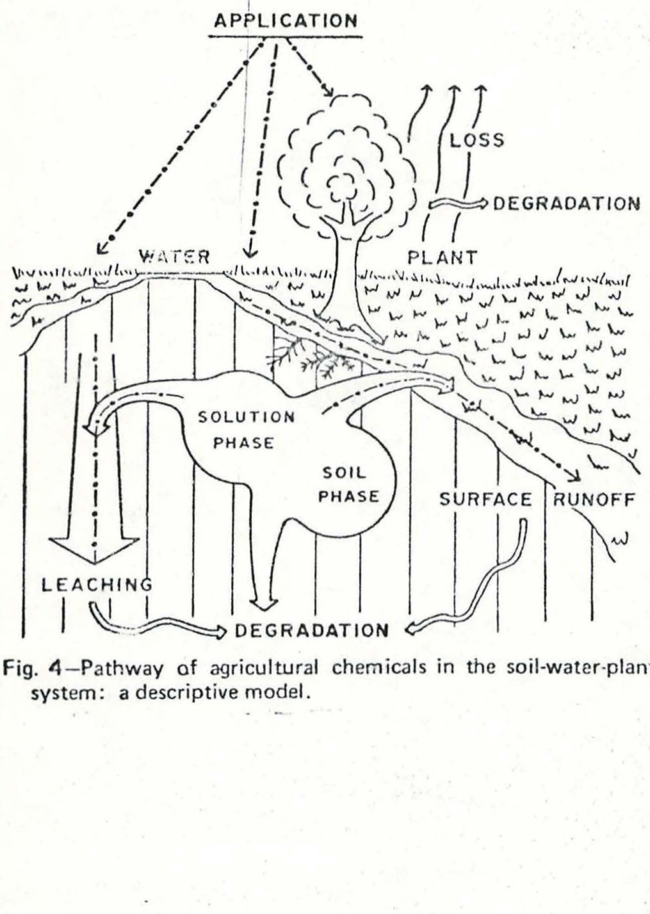

Fig. 4—Pathway of agricultural chemicals in the soil-water-plant system: a descriptive model.

TABLE 2. INFORMATION REQUIREMENT FOR THE MODEL

Chemical

1. Breakdown coefficient, day^{-1}
2. Adsorption coefficient, ratio of concentrations
3. Application rate, kg/ha
4. Relative preference for size fractions
5. Nitrogen mineralization potential, kg/ha

Physical

6. Dispersion distribution factor, cm
7. Field capacity, cc water/cc soil
8. Porosity, cc water/cc soil
9. Texture of soil
10. Bulk density, g/cc

Hydrological

11. Infiltration before runoff, cm
12. Infiltration during runoff, cm
13. Runoff, cm
14. Ratio of lateral to vertical flow
15. Evapotranspiration between storms, cm
16. Average temperature between storms, °C
17. Average soil moisture between storms

Erosional

18. Interrill erosion, tons
19. Rill erosion, tons
20. Fraction of area in rills
21. Depth of rills, cm
22. Deposition, tons
23. Texture of sediment

Frere's model separates the watershed into a number of compartments. Each compartment is uniform with respect to crops, soil type, hydrology, and erosion. Thus, each compartment can be treated as a unit for chemical behavior with inflows and outflows to the other compartments. He uses two major classes for the processes controlling the behavior of chemicals in soils. These conditions are (i) during storms when there is movement, and (ii) between storms when movement is negligible. If movement occurs in

more than one soil layer then new parameters must be established for each of the layers affected. This model is designed to predict the concentration in the runoff and the location of the chemical remaining on the watershed.

Although this agricultural model is only in the preliminary stages of development, it is hoped that a model of this type will be available in the near future. Such a model might be adaptable to assessment of the chemical water quality impacts of proposed transportation systems. This would be a valuable tool in the planning phases of the project.

Searches for chemical quality information has not been limited to agricultural sources. Computer-aided review of the highway engineering field has led to a promising data source--the State of California. The California Division of Highways is currently conducting an extensive study to quantify the effects of highway facilities on water quality. Correspondence and discussions with principal investigator, Richard Howell (8), will continue. It is hoped that data and information obtained for high-standard highways in California will be adaptable to the haul road project.

FUGITIVE DUST-WIND EROSION

Fugitive dust, a component of wind erosion, is a serious problem in many areas of the world. In the United States, the term brings to mind the days of the dust bowls in the Midwest and Southwest. Wind erosion lowers soil productivity, damages plants, and fills road ditches, culvert inlets and fence rows with soil. Lately, concern has been expressed by highway people that wind blown soil particles will clog open-graded pavements,

thereby reducing or eliminating the water infiltration concept. Dust associated with wind erosion obscures visibility, fouls machinery, increases domestic and business costs and affects the respiratory and optic systems of humans and animals.

Research of wind erosion has been an extensive endeavor of the U.S. Department of Agriculture, comparable to that of water erosion. As expected, USDA has been primarily concerned with gross soil losses from farmland and its effects on productivity. Separation of the fugitive dust component from wind erosion has not been extensively researched. The Southwestern states, particularly New Mexico, have focused their efforts on fugitive dust borne from the interaction of vehicle tires on unpaved roads. Fugitive dust, as a result of entrainment of dust blowing across the road surface and cut-and-fill surfaces, has not received much attention. This is not to say that this is not important. It is possible that in certain semi-arid areas, wind exceeds water as the dominant erosion inducing force.

In view of the aforementioned, it is proposed that the effects of wind be broken into two categories. One category will deal with the roadway surface and will study the fugitive dust resulting from vehicle contact. Amounts of such dust likely exceed the amounts entrained from wind blowing across a roadway surface, and, therefore, are of primary importance. Results of studies such as those of New Mexico (1,2) and California (3) can then be utilized. The other category will be directed to determination of wind erosion from cut-and-fill surfaces and other disturbed surfaces. Application of the agricultural wind-erosion equation is being evaluated. Further refinement of the model to delineate the suspended particulate portion will then be attempted.

Wind Erosion Equation

In the wind-erosion process, wind exerts sufficient forces on the surface of the ground to dislodge and transport the most easily detachable soil particles or sand grains. Particles 0.1 to 0.5 mm in diameter rise almost vertically and return, at an angle, to the surface (saltation). Larger particles roll and slide along the ground surface (creep). Particles smaller than 0.1 mm may enter suspension. Comprehensive descriptions of these processes and erosion mechanics are given by Skidmore (4) and Sultan (5).

Studies of the wind-erosion process and its control led to the development of a wind erosion equation (6,7). The equation is a functional relationship developed to determine potential erosion from a particular field and to design field conditions necessary to reduce potential erosion to a tolerable amount. The equation is as follows:

$$E = f(I', K', C', L', V)$$

where:

- E is the potential averate annual soil loss, tons/acre
- I' is a soil erodibility index
- K' is a soil-ridge roughness factor
- C' is a climatic factor
- L' is field length along the prevailing wind erosion direction
- V is equivalent quantity of vegetative cover

In more detail:

Erodibility Index, I', is indicative of ease of detachment and transport of a soil by wind. From wind tunnel tests, relative erodibilities of soils, reasonably free from organic residues, were determined to be a function of apparent specific gravity and of proportions of dry soil aggregates in various sizes (4). Clods larger than 0.84 mm in diameter were nonerodible. Since then, 1950, the nonerodible soil fraction greater than 0.84 mm, as determined by dry sieving, has been used to indicate erodibility of soil by wind. During severe wind erosion seasons of the mid-1950's, Chepil (8) studied 69 fields in Kansas and eastern Colorado to determine relative field erodibilities for correlation.

Ridge Roughness Factor, K', is a measure of the influence of surface roughness on intensity of drifting dune materials and cultivated soils. Initial intensity of drifting has been found to be much less over a ridged than over a smooth surface. Ridging cultivated soils reduced the severity of drifting, but ridging highly erosive dune materials was only temporarily beneficial. The rate of flow was found to vary inversely with surface roughness.

Climatic Factor, C', is an index of average rate of soil movement by wind as influenced by moisture content in surface soil particles and average windspeed. The soil-moisture term of the C'-factor was developed on the concept that erodibility varies inversely with the equivalent moisture in surface soil particles (4). The windspeed term of the C'-factor is based on the rate of soil movement being proportional to windspeed cubed.

Field Length, L'. The rate of soil movement has been found to begin with zero on the windward side of fields and to increase with distance downwind (4). If the field is large enough, soil flow reaches a maximum that a wind of a given velocity can carry. Relationships between field erodibility and field length are taken into account in the L'-factor term.

Vegetative Factor, V, indicates the value of crop residue for controlling wind erosion. Siddoway, Chepil and Armbrust (9) quantified the specific properties of vegetative covers influencing soil erodibility and developed regression equations that relate soil loss to amounts, types and orientation of vegetative covers, wind velocity and soil cloddiness.

Utilization of the wind equation involves procedures similar to those discussed for the universal soil loss equation for water. These procedures are thoroughly discussed by the Utah State group (10). Their approach to the wind loss equation is being evaluated for application to this surface mining project.

Skidmore (4) discusses a computer solution to the wind loss equation, thus avoiding the many tables and figures required to solve the functional relationships of the equation. Review of this solution will be a necessary task of this project.

In brief, once again advantage is being taken of the efforts of agriculturalists. These efforts date back to the late 1930's and early 1940's and represent much laboratory and field experimental work. This research project has only begun to sift through the available information on the subject of wind erosion.

Suspended Particulates-Dust

As previously stated, fugitive dust is a product of wind erosion, but is being treated separately to accommodate a focus on the studies of the Southwest and other emission factor type studies.

Review of the existing literature indicates that most, if not all, of the research to date has been directed towards the development of emission factors. Empirical expressions for emission factors are developed that may be adapted in a methodology to predict fugitive dust concentrations for a specific project. The wind loss equation, per se, is not designed for air pollution emission inventories; the values established by the equation indicate total gross soil movement, including particles which roll or jump along the ground as well as particles which become airborne and thus become part of the atmospheric aerosol burden.

New Mexico was one of the forerunners of dust emission studies. Early studies in the Albuquerque area with a 30 mph test car on an unpaved road yielded an emission factor in the range of 0.5-0.7 lb/vehicle mile. This was followed by a study by senior engineering students (U. of New Mexico)(11) who found a factor for particles smaller than 6 microns (i.e., particles which would remain suspended under dry, windy conditions) was 0.93 lb/vehicle-mile. Additional studies have followed by PEDCo-Environmental (12) in New Mexico and Arizona. Table 3 (13) summarizes the results of these studies and shows the kinds of information and data that are available.

From these studies have evolved the following empirical expression for the quantity of fugitive dust emissions from an unpaved road, per vehicle mile (14)

Table 3 TESTS OF EMISSIONS FROM UNPAVED ROADS

Site	Type of Road	Vehicle Speed (mph)	Sampler Type	Sampler Location	No. of Tests	Passes per Test	Emission Factor (lb/vehicle-mile)	Dust Size Cut-Off
Bernalillo County, New Mexico	Dirt	30	Small filter	In plume	2	--	0.5 - 0.7	--
University of New Mexico	Dirt	25	Hi-vol filter Rotorod	60-90 ft from road	2	50	0.93 0.04	< 6 μm < 3 μm
Santa Fe, New Mexico	Dirt	15	Beta gauge	50-300 ft from road	1	150	0.67	--
		25	Hi-vol filters		1	240	1.0	--
		35	Hi-vol cascade impactor		3	200	2.0	--
		40			1	130	3.5	--
Poweshiek County, Iowa	Dirt	--	Dustfall containers	Shoulder to 500 ft from road	1	3,000	5.5	--
Duwamish Valley, Washington	Gravel	10	Isokinetic cascade impactor	7 ft behind automobile	2	--	2.2 0.41 0.11	-- < 10 μm < 2 μm
		20			25	--	8.5 2.3 0.29	-- < 10 μm < 2 μm
		30			2	--	13.9 5.2 0.43	-- < 10 μm < 2 μm
	Gravel	20			1	--	8.8 2.4	-- < 10 μm

$$E = (0.81s)\left(\frac{S}{30}\right)\left(\frac{365-W}{365}\right)$$

where: E = Emission factor, pounds per vehicle and mile

s = Silt content of road surface material, percent

S = Average vehicle speed, miles per hour

W = Mean annual number of days with 0.01 in. or more of rainfall (Fig. 5)

In the typical speed range on unpaved roads, 30-50 mph, the field measurements indicate that emissions are directly proportional to vehicle speed. Limited field measurements further indicate that vehicles produce dust in proportion to the number of wheels. For roads with a significant volume of vehicles with six or more wheels, the traffic volume should be adjusted to the equivalent volume of four-wheeled vehicles (14). Attempts will be made to correlate the above information with data from heavy equipment studies or construction sites, in hopes of representing the haul road condition.

Dust emissions from unpaved roads have been found to vary in direct proportion to the fraction of silt (particles smaller than 75 microns--as defined by AASHTO) in the road surface material (13). The silt fraction is determined by measuring the proportion of loose, dry surface dust that passes a 200 mesh screen. The silt content of gravel roads averages about 12 percent, and the silt content of a dirt road may be approximated by the silt content of the parent material in the area (13).

Unpaved roads have a hard, nonporous surface that dries quickly after a rainfall (14). The temporary reduction in emissions because of rainfall

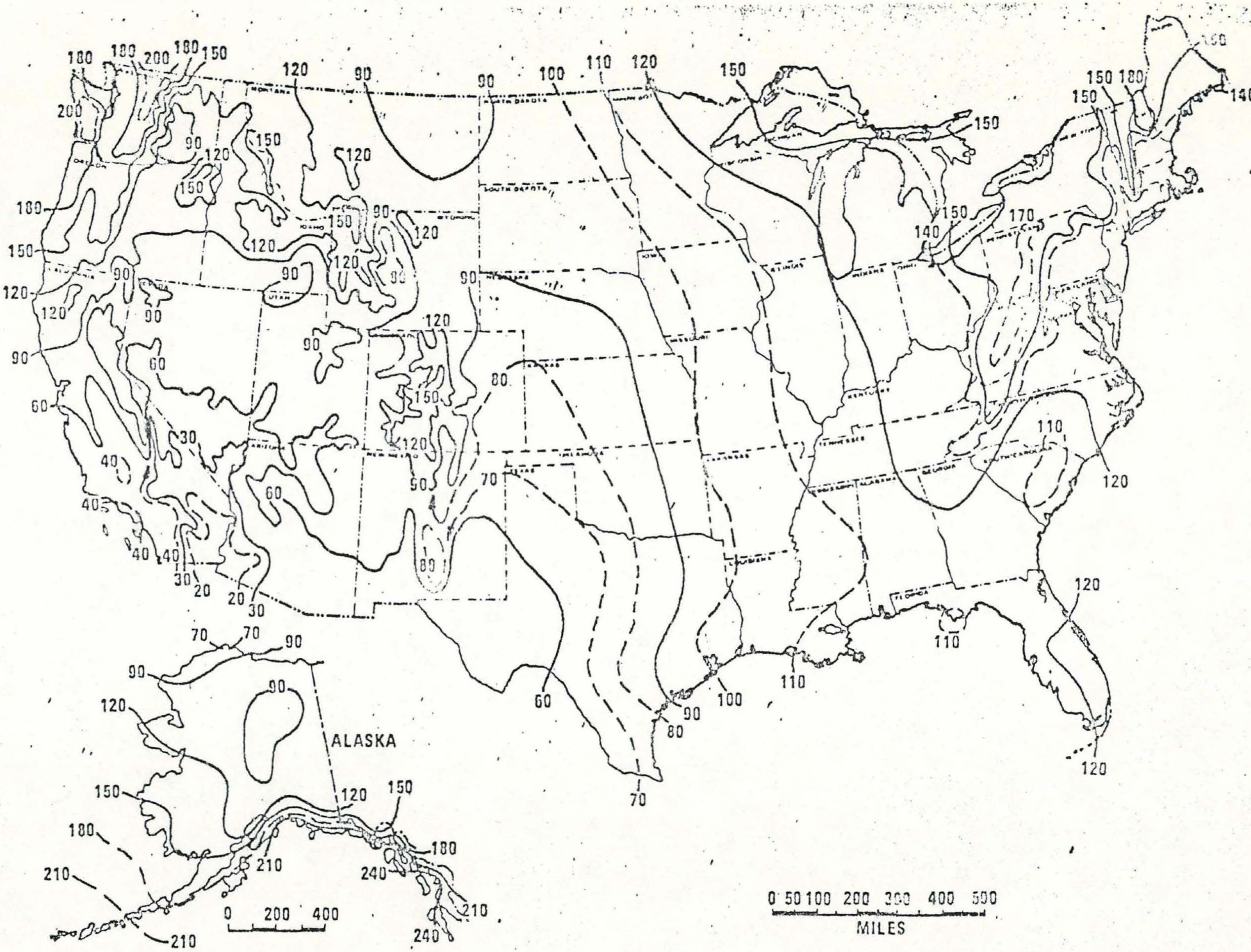

Figure 5 Mean number of days with 0.01 inch or more of precipitation in United States.

may be accounted for by neglecting emissions on "wet" days, that is, days with more than 0.01 inches of rainfall. Note that no provision is made in the equation for pre-existing moisture conditions of the surface.

It appears that a significant amount of emission studies have been done on unpaved roads. In addition, California is currently performing measurements on highway construction projects as part of their studies on environmental effects of highways (3). These dust studies, coupled with the aforementioned studies, will be used to formulate a model for haul roads. Difficulties expected include the formulation of equivalency factors to extrapolate emission factors obtained from previous studies to the unique and diverse traffic connected with mining haul roads.

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PART 2

A SIMPLIFIED MODEL OF THE DAMMING EFFECTS OF EMBANKMENTS ON GROUNDWATER

by

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July 1976

A SIMPLIFIED MODEL OF THE DAMMING EFFECTS OF EMBANKMENTS ON GROUNDWATER

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INTRODUCTION

The dead weight of road embankments produces consolidation of underlying soil strata which reduces permeability and thus partially obstructs the natural flow of groundwater. When the direction of groundwater flow is transverse or strongly oblique to the major axis of the embankment, the consolidated foundation soil may have a distinct damming effect on the groundwater as evidenced by a rise in the water table on the "upstream" side of the embankment. In extreme cases, the water table may rise to the ground surface or higher and produce either a marsh or a lake of seasonal or permanent duration.

An exact solution for the amount of water table rise would be a formidable task involving non-steady, three-dimensional groundwater flow through non-homogeneous, non-isotropic soils consolidated to different permeabilities throughout the embankment foundation zone.

DEFINITIONS AND NOMENCLATURE

This paper describes a greatly simplified yet semi-rational model for calculating a rough estimate of the water table rise on the "upstream" side of an embankment constructed on a homogeneous soil deposit having a uniform coefficient of permeability, k_1. The soil is underlain by an impervious boundary plane which dips in a direction perpendicular to the axis of the

embankment. It is assumed that steady-state groundwater conditions exist and that the unperturbed water table and the ground surface are both parallel to the impervious boundary which makes an angle β with the horizontal.

The zone of variably consolidated soil beneath the embankment is replaced, in the simplified model, by a neat rectangular prism of length L, in the direction of flow, of uniformly consolidated soil which has a uniform coefficient of permeability, k_2, which is less than k_1. These conditions are illustrated in Figure 1 wherein the prism of reduced permeability is represented as BCDE, and the maximum water table rise is shown as ΔZ. Figure 1 also defines certain key dimensions and their algebraic symbols which will be used throughout the report.

For the highly idealized conditions stated, an exact solution for the final location of the water table or top flow line would be possible but probably not worth the trouble because of the high degree of idealization and also because one additional major simplifying assumption will reduce the problem to an easy exercise.

DERIVATION

Theoretical details of the top flow line geometry in and adjacent to prism BCDE are illustrated in Figure 2. Taylor [1] and others have shown that flow lines are bent or deflected as indicated in Figure 2 when seeping water crosses boundaries such as BC and DE which separate the zones of differing permeability.

The one remaining major simplifying assumption referred to earlier consists of replacing the curved top flow line in prism BCDE by an "equivalent"

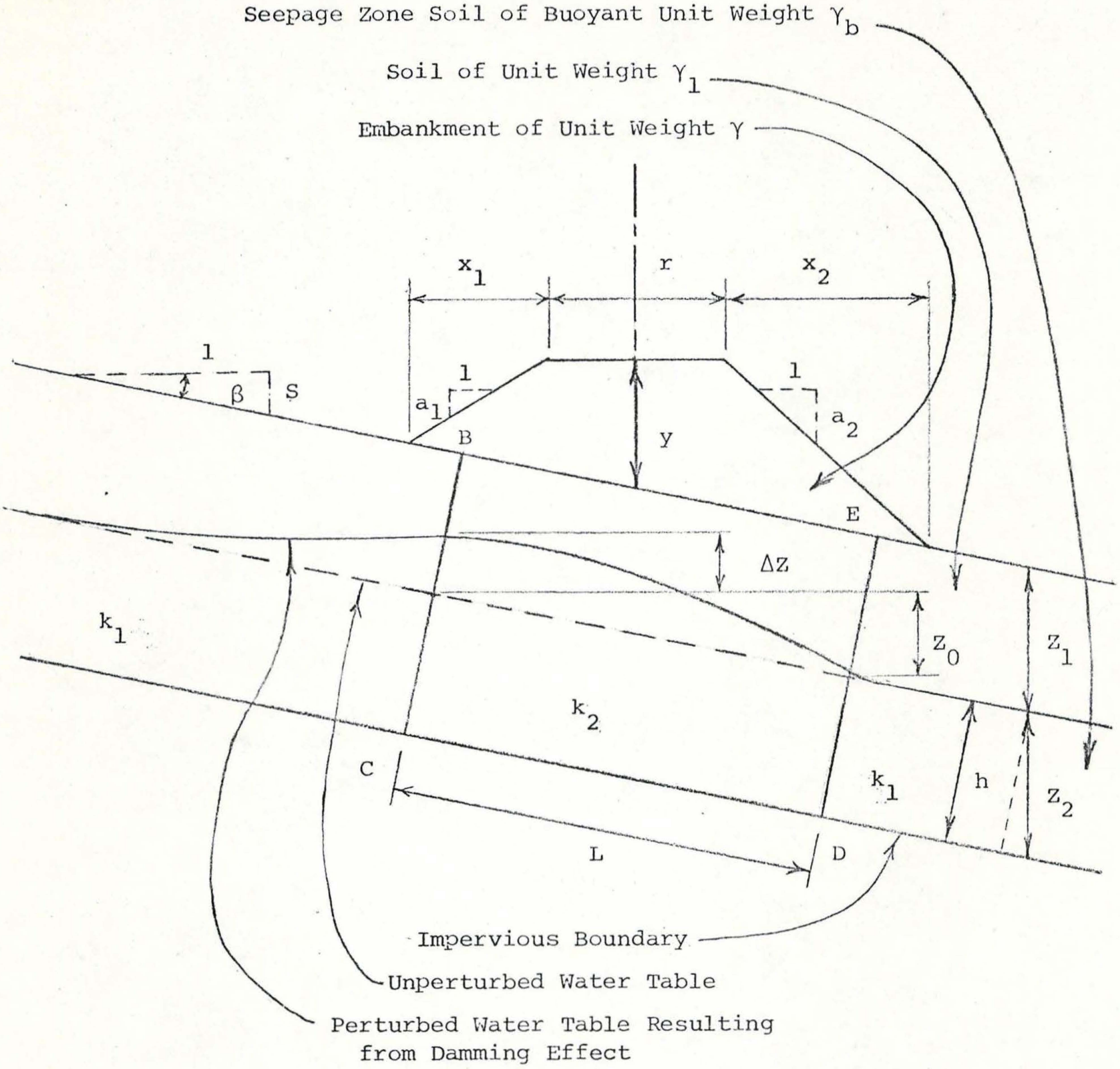

Figure 1. Elements of the Simplified Model.

$$k_1 > k_2$$

$$\frac{k_1}{k_2} = \frac{\tan \alpha_1}{\tan \alpha_2} = \frac{\tan \theta_1}{\tan \theta_2}$$

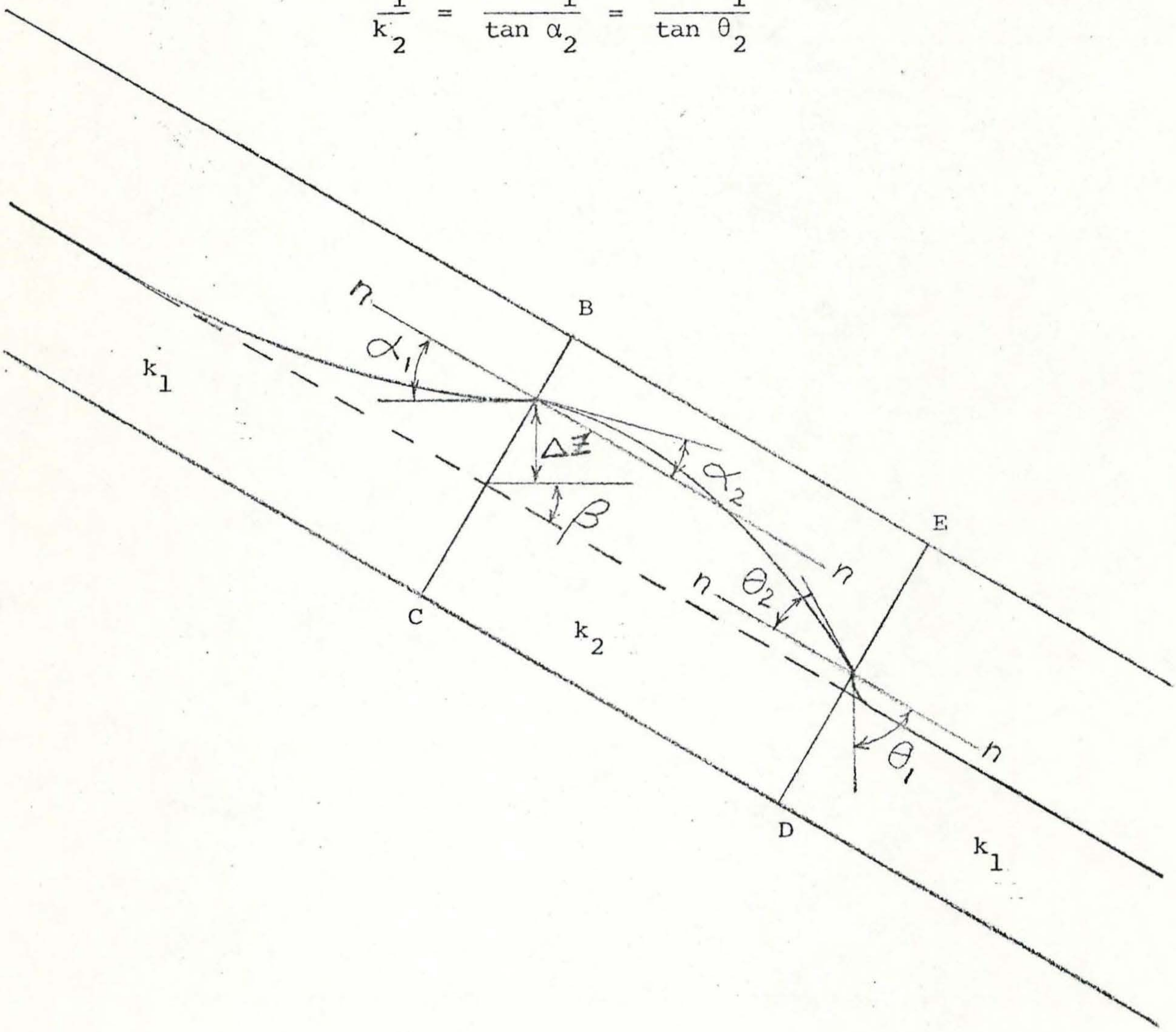

Figure 2. Theoretical Details of Top Flow Line Through Prism BCDE.

straight-line top flow line, FG, as shown in Figure 3. An estimate of the maximum water table rise, ΔZ, may then be calculated as follows: Consider a representative strip of unit thickness, perpendicular to the figure, and apply Darcy's Law to calculate the groundwater flow rate across any section such as MN, outside the zone of water table perturbation. This flow rate may be expressed as

$$Q = k_1 i_1 A_1 \tag{1}$$

For the steady-state groundwater flow condition, the flow rate Q must be the same at every cross-section, and the cross-section which best represents the "average" conditions in prism BCDE is at the mid-length location where we may write

$$Q = k_2 i_2 A_2 \tag{2}$$

Since Q is constant, Equations (2) and (1) may be equated, which yields

$$k_2 i_2 A_2 = k_1 i_1 A_1 \tag{3}$$

In Equation (3), the flow area A_1 is equal to hxl, or merely h, which is the thickness of the seepage zone either upstream or downstream from the zone of perturbation. Similarly the flow area A_2 is equal to $h+\Delta h/2$, as shown in Figure 3, where Δh is the maximum increase in the thickness of the seepage zone.

The hydraulic gradient i_1 is equal to $\sin\beta$ where β is the slope angle of the unperturbed water table. In terms of the dimensions shown in Figure 3, $\sin\beta$ may be expressed as: $\sin\beta = Z_0/L$, where Z_0 is the head loss which occurs over a flow length L, anywhere outside the perturbed zone.

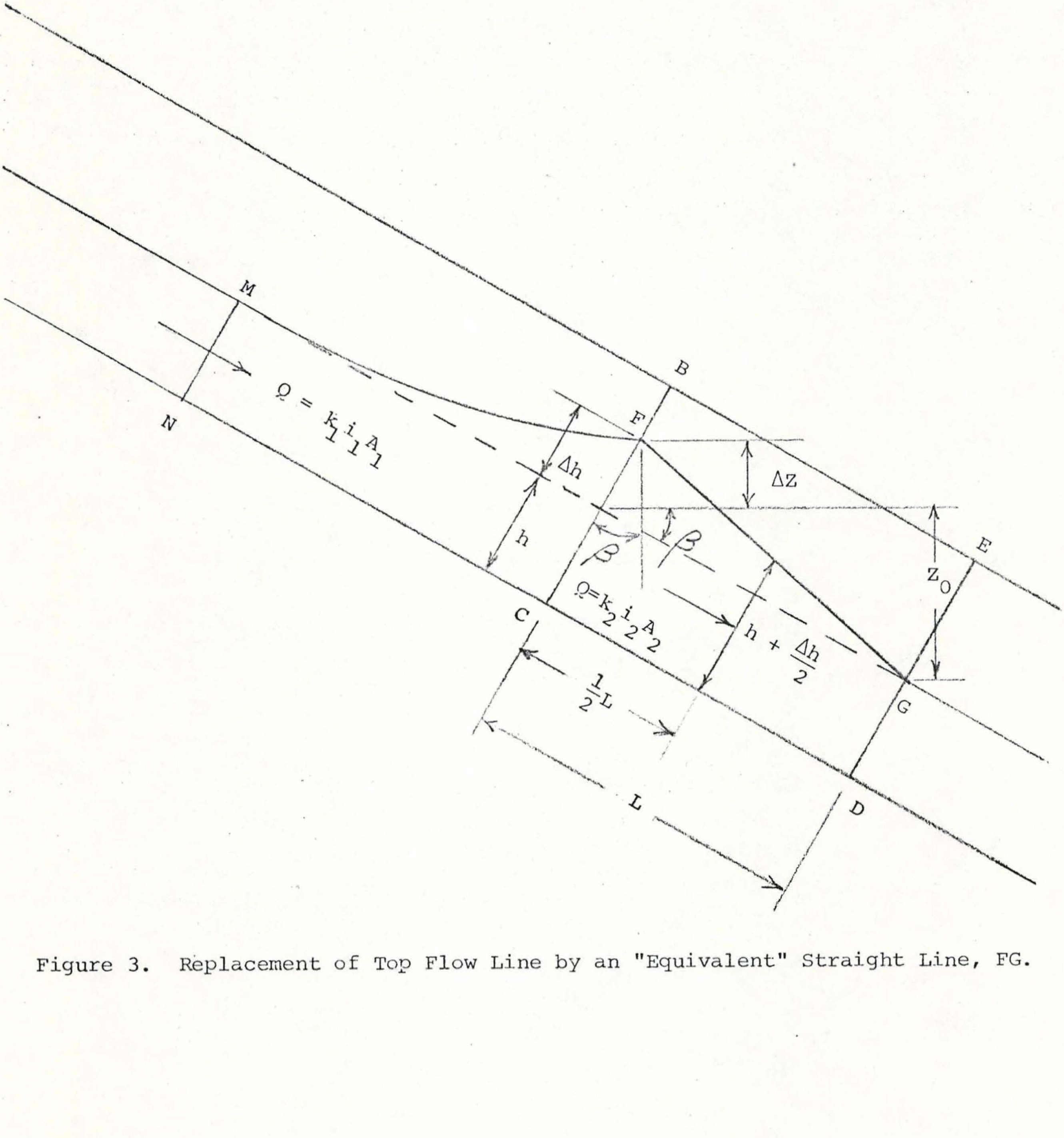

Figure 3. Replacement of Top Flow Line by an "Equivalent" Straight Line, FG.

The total head loss that occurs as the water flows through prism BCDE may be expressed as $Z_0+\Delta Z$ as indicated in Figure 3. This head loss occurs over an average flow distance of approximately L. Therefore, the "average" hydraulic gradient, i_2, in the flow area A_2, may be expressed as $(Z_0+\Delta Z)/L$.

After making all of the above-mentioned substitutions into Equation (3), we obtain

$$k_2 \frac{Z_0 + \Delta Z}{L} (h+ \frac{\Delta h}{2}) = k_1 \frac{Z_0}{L} h \tag{4}$$

From Figure 3 it is evident that $\Delta h=\Delta Z/\cos\beta$. We may make this substitution into Equation (4) and perform a few simple algebraic manipulations to obtain

$$(\Delta Z)^2 + (Z_0+2h\cos\beta)(\Delta Z) - 2Z_0 h(\frac{k_1}{k_2} -1)\cos\beta = 0 \tag{5}$$

At this stage it is appropriate to express Z_0 in terms of L and β by substituting $Z_0=L\sin\beta$ into Equation (5). The resulting equation is

$$(\Delta Z)^2 + (L\sin\beta+2h\cos\beta)(\Delta Z) - 2Lh(\frac{k_1}{k_2} -1)\sin\beta\cos\beta = 0 \tag{6}$$

This is an ordinary quadratic equation of the form $a(\Delta Z)^2 + b(\Delta Z) + c = 0$ which may be solved for ΔZ by the well-known quadratic formula

$$\Delta Z = \frac{-b \pm\sqrt{b^2-4ac}}{2a} \tag{7}$$

It is apparent from Equation (6) that the coefficients a, b, and c may be expressed as

$$a = 1$$

$$b = L\sin\beta + 2h\cos\beta$$

$$c = -2Lh\left(\frac{k_1}{k_2} - 1\right)\sin\beta\cos\beta$$

Substituting these values into Equation (7) we obtain

$$\Delta Z = \frac{-(L\sin\beta+2h\cos\beta) + \sqrt{(L\sin\beta+2h\cos\beta)^2 + 8Lh\left(\frac{k_1}{k_2} - 1\right)\sin\beta\cos\beta}}{2} \qquad (8)$$

The negative sign was dropped from the radical term in Equation (8) because the positive square root is the only one that will yield a meaningful positive value for ΔZ.

Equation (8) represents the completed derivation in a convenient, usable format. The meaning of each symbol is recapitulated for the convenience of the reader, as follows: ΔZ is the maximum rise in the elevation of the perturbed water table on the upstream side of an idealized compressed rectangular prism of length L in the direction of groundwater flow; β is the slope or dip angle of the unperturbed water table; h is the thickness of the unperturbed seepage zone; k_1 is the coefficient of permeability of the uncompressed soil upstream and downstream from the compressed zone; and k_2 is the coefficient of permeability of the soil in the compressed zone, k_2 being smaller than k_1.

Tentatively, Equation (8) must be regarded as a rough approximation, primarily because of the fact that the straight line, FG in Figure 3, is only a rough approximation of the true curved top flow line in prism BCDE.

A series of relatively simple laboratory experiments, using a rectangular flume in a fluid mechanics laboratory, could be carried out to

determine how accurately or inaccurately Equation (8) predicts the true damming effect for the idealized soil conditions portrayed in Figures 2 and 3. Project personnel are planning to conduct such experiments in the future.

PRACTICAL PROBLEMS IN THE APPLICATION OF EQUATION (8)

If it turns out that the equation does a satisfactory job of predicting ΔZ in an idealized situation which duplicates the soil conditions portrayed in Figures 2 and 3, there still remains some serious problems in using it to predict ΔZ in complicated, real-life, field situations; the main problems being the determination of the proper values to use for the length L and for the permeability ratio, k_1/k_2.

Tentatively, it is recommended that the length L of the idealized compressed zone be estimated by representing the embankment load by an idealized "equivalent" uniform strip load and then applying the "two to one load spread" method down to an appropriate depth, Z, below the original ground surface. Relevant details are illustrated in Figures 4 and 5.

In Figure 4, the magnitude of the equivalent strip load is given as $q_0 = \gamma y \cos\beta$ wherein q_0 is the vertical force per unit of actual inclined surface area. In Figure 5, σ_0 is shown as the normal component of q_0, i.e.,

$$\sigma_0 = q_0 \cos\beta = \gamma y \cos^2\beta \qquad (9)$$

where γ is the unit weight of the embankment soil and y is the center-line height of the embankment. The lateral extent of q_0 and σ_0 is tentatively

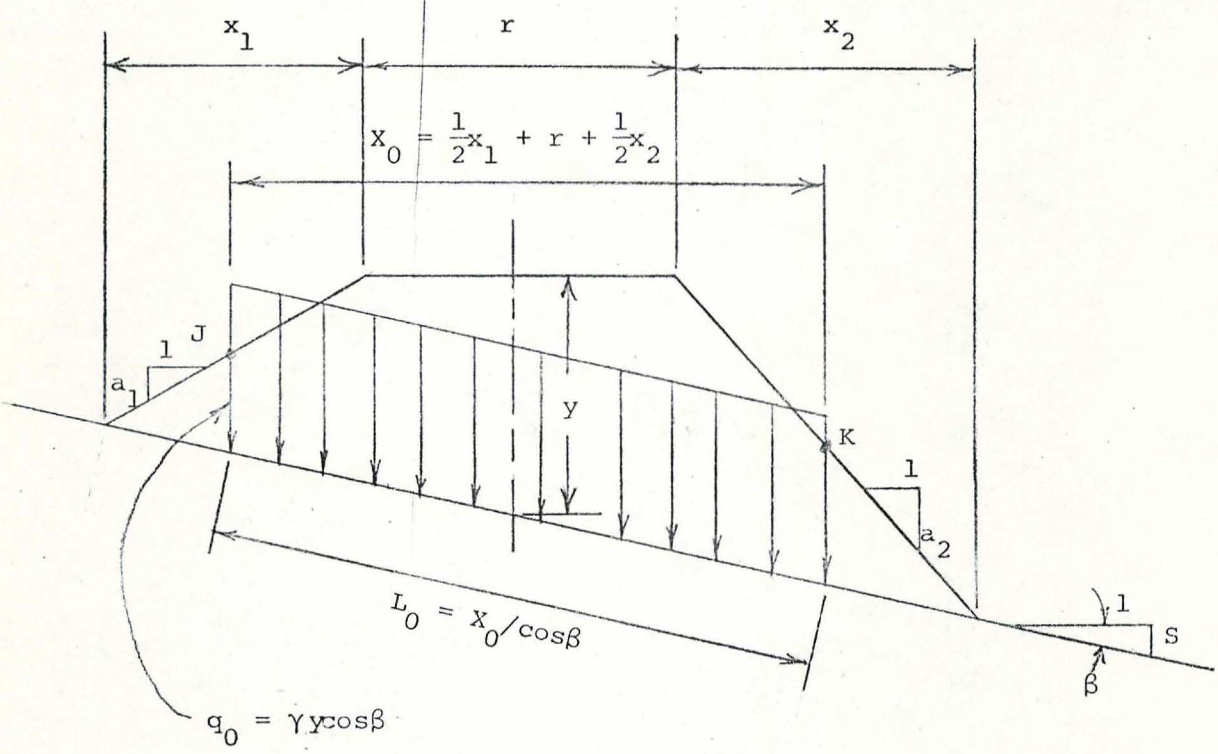

Figure 4. Representing the Embankment by an "Equivalent" Strip Load, q_o.

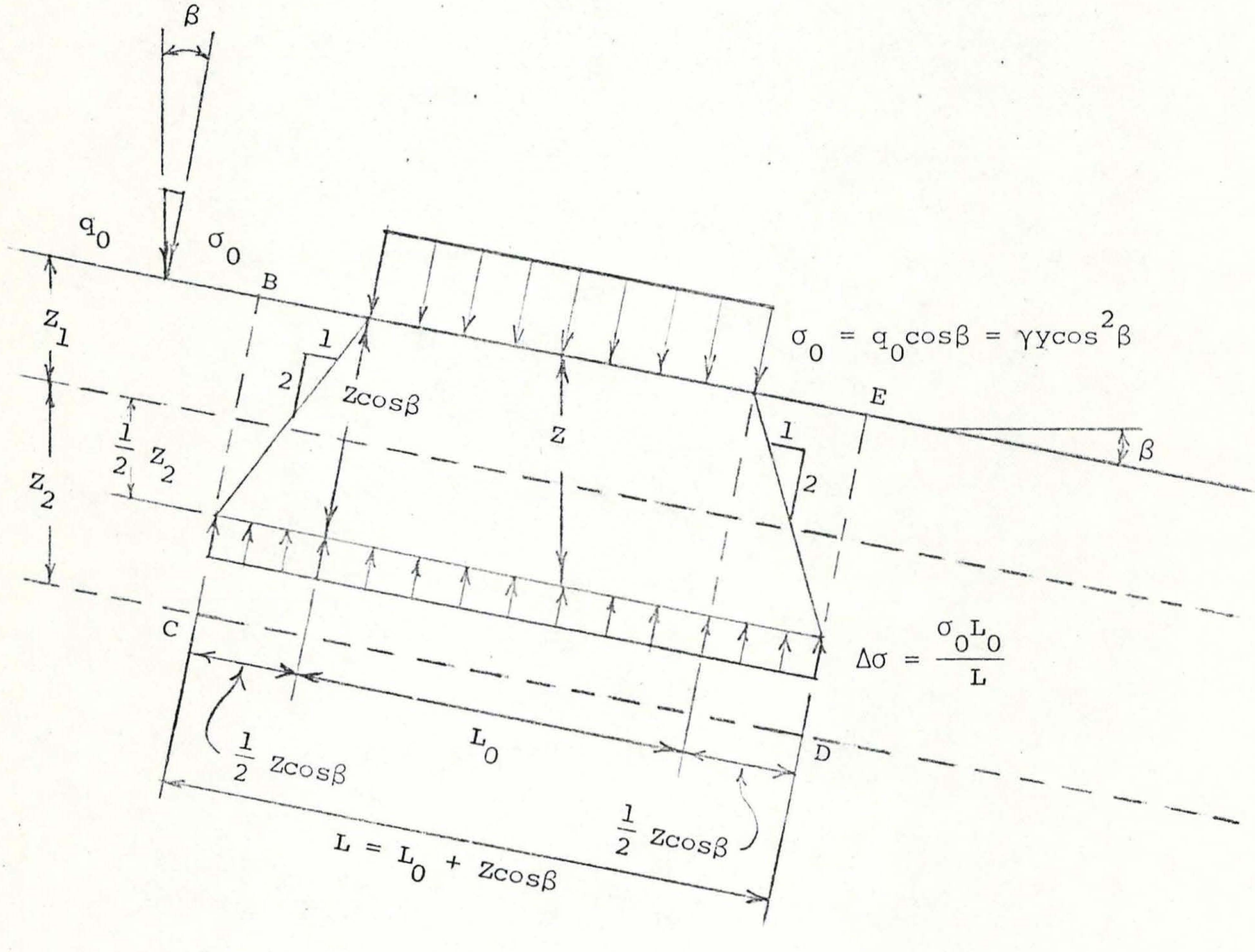

Figure 5. Application of "Two to One Spread" Approximation to Determine L and $\Delta\sigma$.

assumed to extend between the midpoints, J and K, of the embankment side slopes as depicted in Figure 4. In other words, the strip load exists over a horizontal distance

$$X_0 = r + \frac{1}{2}x_1 + \frac{1}{2}x_2 \tag{10}$$

which corresponds to a ground surface slope distance of

$$L_0 = X_0/\cos\beta \tag{11}$$

Figure 5 shows the surface consolidating pressure, σ_0, of lateral extent L_0, spreading out with depth according to the "two to one spread" concept until, at depth Z, the average consolidating pressure increase is $\Delta\sigma$ acting on length L.

It is tentatively recommended that Z be assumed to extend down to the mid-depth of the unperturbed seepage zone, i.e.,

$$Z = Z_1 + \frac{Z_2}{2} \tag{12}$$

In Figure 5, it is evident that the thickness corresponding to the depth Z, is $Z\cos\beta$, and the length L is

$$L = L_0 + Z\cos\beta \tag{13}$$

This is the value of L recommended for use in Equation (8).

Also consistent with the "two to one spread" concept, we may write

$$\Delta\sigma = \frac{\sigma_0 L_0}{L} = \frac{(\gamma y\cos^2\beta)L_0}{L_0 + Z\cos\beta} \tag{14}$$

In Figure 5, if the embankment side slopes are equal, i.e., $a_1 = a_2 = a$, then it may be shown that

$$L_0 = \frac{r}{\cos\beta} + \frac{ay + \frac{S^2 r}{2}}{(a^2 - S^2)\cos\beta} \qquad (15)$$

This is a convenient expression, when applicable, to use for calculating the value of L_0 to use in Equations (13) and (14). If the side slopes are not equal, it is first necessary to calculate x_1 and x_2 as follows:

$$x_1 = \frac{y - \frac{1}{2} Sr}{a_1 + S} \qquad (16)$$

$$x_2 = \frac{y + \frac{1}{2} Sr}{a_2 - S} \qquad (17)$$

These values may be used in Equation (10) to calculate X_0 which then enables one to calculate L_0 using Equation (11).

The second major practical problem in the application of Equation (8) lies in determining the value of the permeability ratio, k_1/k_2. A direct approach would be to take undisturbed samples of the foundation soil and measure the downslope coefficient of permeability, k_1, after first letting the samples reach equilibrium under a pressure equal to the in-place effective overburden pressure, $\bar{\sigma}_1$. For a sample taken at mid-depth in the unperturbed seepage zone, the value of $\bar{\sigma}_1$ would be

$$\bar{\sigma}_1 = (\gamma_1 Z_1 + \frac{1}{2} \gamma_b Z_2)\cos^2\beta \qquad (18)$$

The same samples would then be allowed to consolidate under the additional pressure anticipated from the proposed embankment before measuring the final coefficient of permeability, k_2. For a sample taken at mid-depth in

the unperturbed seepage zone, the pressure increase would be $\Delta\sigma$ from Equation (14) and the final effective consolidating pressure, $\bar{\sigma}_2$, would be

$$\bar{\sigma}_2 = \bar{\sigma}_1 + \Delta\sigma \tag{19}$$

A minor error in the use of Equation (19) is that it ignores the buoyance effect caused by the upward perturbations of the water table in the compressed zone BCDE.

Observations at applicable field sites will be needed to determine whether or not Equation (8), used in the fashion suggested above, is a satisfactory tool for predicting water table rise on the upstream side of embankments. If it shows promise, efforts should then be made to determine the most appropriate methods to evaluate L and k_1/k_2 for use in the equation. The methods suggested above are arbitrary and tentative and susceptible to considerable refinement.

THEORETICAL APPROACH TO ESTIMATE k_1/k_2

In the absence of field or laboratory measurements of k_1 and k_2, it may be possible, in some cases, to calculate a sufficiently accurate value of k_1/k_2 by using certain well-established relationships available in the soil mechanics literature.

First, let e_1 represent the in-place or <u>in situ</u> void ratio of a soil stratum which has consolidated under the existing effective overburden pressure, $\bar{\sigma}_1$. If the consolidating pressure is then increased by an amount $\Delta\sigma$, the final effective pressure becomes $\bar{\sigma}_2$ which is equal to $\bar{\sigma}_1 + \Delta\sigma$. The final void ratio of the soil is e_2, after it has consolidated under the pressure $\bar{\sigma}_2$, and the change in void ratio, Δe, is equal to $e_2 - e_1$. Δe may

be expressed in terms of the initial and final effective pressures as follows:

$$\Delta e = C_c \log\left(\frac{\bar{\sigma}_1}{\bar{\sigma}_2}\right) \tag{20}$$

In the case of a normally consolidated soil, C_c is a soil property called the compression index and it is a constant over a relatively large pressure range.

As the soil experiences the void ratio change, Δe, its coefficient of permeability changes from an initial value, k_1, to a final value, k_2. Researchers have established that the interrelationship is validly represented by the equation

$$\Delta e = C_k \log\left(\frac{k_2}{k_1}\right) \tag{21}$$

In this equation, C_k is a soil property which is constant for an undisturbed soil as its permeability changes as a result of consolidation. In this report, C_k will be called the permeability index.

Equations (20) and (21) may be equated to each other which yields

$$C_k \log\left(\frac{k_2}{k_1}\right) = C_c \log\left(\frac{\bar{\sigma}_1}{\bar{\sigma}_2}\right) \qquad \text{or}$$

$$\log\left(\frac{k_2}{k_1}\right) = \frac{C_c}{C_k} \log\left(\frac{\bar{\sigma}_1}{\bar{\sigma}_2}\right) \tag{22}$$

taking the antilog of both sides of Equation (22) we obtain

$$\frac{k_2}{k_1} = \left(\frac{\bar{\sigma}_1}{\bar{\sigma}_2}\right)^{C_c/C_k} \tag{23}$$

The reciprocal of Equation (23) is

$$\frac{k_1}{k_2} = \left(\frac{\bar{\sigma}_1}{\bar{\sigma}_2}\right)^{-C_c/C_k} \tag{24}$$

If the value of C_c/C_k is known, then the value of k_1/k_2 may be calculated from Eq. (24) and used in Eq. (8).

According to Mesri and Rokhsar [2], C_c/C_k often lies in the range of $\frac{1}{2}$ to 2, with the most common values between $\frac{1}{2}$ and 1. Berry and Wilkinson [3] also suggest the limits of $\frac{1}{2}$ to 2 for most natural soils. Experienced engineers may prefer to estimate C_c and C_k separately and then calculate the ratio.

Values of C_k may be deduced for a wide variety of soils from Figure 19.5 in Lambe and Whitman [4]. In that figure, a value of 0.7 appears typical for a wide range of soils including sands, silts, and clays.

Most soil mechanics textbooks give methods for estimating the compression index, C_c. A normally consolidated silt or clay, having relatively high compressibility, might have a compression index of approximately 0.3. A fairly typical value of C_c/C_k for a highly compressible silt or clay could therefore be obtained by using $C_c = 0.3$ and $C_k = 0.7$. This yields $C_c/C_k = 3/7$. This value will be used in the illustrative example which follows.

ILLUSTRATIVE EXAMPLE

Consider a soil profile consisting of a 20 foot depth of compressible silt on top of impervious bedrock, with the water table at a depth of 10 feet. In other words, $Z_1 = Z_2 = 10'$. The slope, S, of the ground surface,

is 0.10, which makes β = arctan S = 5.71°. For this value of β, $\sin\beta$ = .0995 and $\cos\beta$ = .995. The value of C_c/C_k for the silt, is 3/7. Above the water table the silt has a unit weight, γ_1, of 115 pcf and below the water table it has a buoyant or effective unit weight, γ_b, of 60 pcf. The road embankment has a height, y, of 20 feet at the center line; a top width, r, of 40 feet; a unit weight, γ, of 130 pcf; and side slopes of 50%, i.e., $a_1 = a_2 = a = 0.5$.

The predicted height of water table rise, ΔZ, may then be calculated as follows:

First calculate the normal component, σ_0, of the equivalent strip load, using Equation (9).

$$\sigma_0 = \gamma y \cos^2\beta = 130(20)(.995)^2 = 2574 \text{ psf}$$

Using Equation (15), L_0 is then calculated to be 82.91'. Z, from Equation (12), is 15'; and L may then be calculated from Equation (13).

$$L = L_0 + Z\cos\beta = 82.91 + 15(.995) = 97.84'$$

Equation (14) will then give the average pressure increase, $\Delta\sigma$.

$$\Delta\sigma = \frac{\sigma_0 L_0}{L} = \frac{2574(82.91)}{97.84} = 2181 \text{ psf}$$

The average initial effective pressure in the seepage zone, $\bar{\sigma}_1$, is calculated from Equation (18).

$$\bar{\sigma}_1 = (\gamma_1 Z_1 + \tfrac{1}{2}\gamma_b Z_2)\cos^2\beta = (115(10) + \tfrac{1}{2}(60)(10))(.995)^2 = 1436 \text{ psf}$$

The final effective consolidating pressure, $\bar{\sigma}_2$, is then calculated from Equation (19).

$$\bar{\sigma}_2 = \bar{\sigma}_1 + \Delta\sigma = 1436 + 2181 = 3617 \text{ psf}$$

The permeability ratio, k_1/k_2, is then calculated from Equation (24).

$$\frac{k_1}{k_2} = \left(\frac{\bar{\sigma}_1}{\bar{\sigma}_2}\right)^{-C_c/C_k} = \left(\frac{1436}{3617}\right)^{-3/7} = 1.4857$$

The thickness, h, of the seepage zone is calculated as:

$$h = Z_2 \cos\beta = 10(.995) = 9.95'$$

All terms in Equation (8) have now been evaluated so we may use it to calculate the water table rise, ΔZ (for the sake of brevity, Equation (8) will not be repeated here).

$\Delta Z = 2.9'$ from Equation (8)

The extent by which the thickness of the seepage zone affects the calculated value of ΔZ was explored by varying the value of Z_2 while holding constant all of the independent factors in the preceding example. The results of these calculations are summarized in Table 1.

Table 1. The Effects of Varying Z_2 in the Illustrative Problem

Related	Height of Seepage Zone, Z_2, in Feet						
Variables	4	6	10	20	30	40	80
h, ft	3.98	5.97	9.95	19.9	29.85	39.8	79.6
Z, ft	12	13	15	20	25	30	50
L, ft	94.85	95.85	97.84	102.81	107.79	112.76	132.66
$\Delta\sigma$, psf	2250	2227	2181	2076	1980	1893	1609
$\bar{\sigma}_1$, psf	1257	1317	1436	1733	2030	2327	3515
$\bar{\sigma}_2$, psf	3507	3544	3617	3809	4010	4220	5124
k_1/k_2	1.552	1.528	1.486	1.398	1.339	1.291	1.175
ΔZ, ft	2.1	2.5	2.9	3.1	3.0	2.8	2.1

DISCUSSION

The most interesting aspect of Table 1 is the very small changes in water table rise that occur when large changes are made in the thickness of the seepage zone. This suggests that it may not be necessary to explore soil conditions to great depth in order to use Equation (8). It appears that a conservative estimate of ΔZ could be made by assuming a value of 20' or 30' for Z_2 when there is no well defined impervious boundary at a shallow depth.

A more serious problem will occur when there are large variations in permeability, and other soil properties, with depth. Detailed recommendations for handling various types of soil profiles will need to be worked out later.

In any situation where the slope, S, is smaller than 0.10, or 10%, the equations will give satisfactory accuracy if one assumes a value of 1 for the cosine of β and a value of S for the sine of β. If these simplifying approximations had been used in working the preceding illustrative problem, the answers would not have changed by any significant amount.

The reader will recognize that the derivation of Equation (8) is based upon the implicit supposition that the perturbed water table does not rise above the original ground surface. This means that Equation (8) cannot be considered to be strictly applicable if the calculated value of ΔZ is larger than $Z_1 \cos^2\beta$. This would correspond to a water table rise of 9.9 feet in the illustrative problem.

Whenever the calculated value of ΔZ exceeds $Z_1 \cos^2\beta$, it is necessary to examine the permeability of the embankment, and surface drainage

features, to determine what will happen. If the embankment is highly permeable, in comparison to the foundation soil, we may conclude that ponding will not occur to any significant depth and the water that rises to the surface will seep through the bottom portion of the embankment and perhaps create a swampy area for a small distance downstream from the embankment, in addition to the swampy area on the upstream side. The results would be essentially the same if the embankment were impermeable and culverts were provided to prevent ponding and to carry the surface water through to the other side. The results would be somewhat similar if the embankment is impermeable and the surface water drains away longitudinally in the side ditch formed by the interesection of the natural ground surface with the upstream side slope, a_1, of the embankment (refer to Figure 1). In this latter case there will not, of course, be a swampy area forming on the downhill side of the embankment but the water flowing longitudinally in the ditch must eventually enter a stream or a culvert or seep back into the ground.

If the permeability of the embankment is essentially the same as that of the compressed foundation soil (and if there are no culverts and no longitudinal surface drainage), it would seem that Equation (8) might still be reasonably applicable and that the depth of surface ponding might be estimated directly from the calculated value of ΔZ, when ΔZ exceeds $Z_1 \cos^2\beta$. However, if the embankment soil is relatively impermeable, it constitutes an additional flow barrier and the actual water table rise should be larger than the value of ΔZ calculated from Equation (8). We could derive a modified version of Equation (8) to handle this special case if future developments indicate that it would be worthwhile.

CLOSURE

This brief paper represents a pilot effort to predict certain hydrologic effects of road embankments by utilizing some basic principles of soil mechanics and seepage. It is hoped that other investigators will be stimulated to criticize and improve upon the mathematical model presented in this report, and perhaps help to verify it or disprove it by comparing observed heights of water table rise with heights predicted from Equation (8).

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